4-14-2013

Length and temperature dependent 1/f noise in vertical single-walled carbon nanotube arrays

Robert A. Sayer
Birck Nanotechnology Center, Purdue University, rsayer@purdue.edu

Jeffrey D. Engerer
Birck Nanotechnology Center, Purdue University, jengerer@purdue.edu

N. S. Vidhyadhiraja
Indian Institute of Science; Jawaharlal Nehru Center for Advanced Scientific Research

Timothy S. Fisher
Birck Nanotechnology Center, Purdue University, tsfisher@purdue.edu

AIP | Journal of Applied Physics

Length and temperature dependent 1/f noise in vertical single-walled carbon nanotube arrays

Robert A. Sayer, Jeffrey D. Engerer, N. S. Vidhyadhiraja, and Timothy S. Fisher

Citation: J. Appl. Phys. **113**, 144306 (2013); doi: 10.1063/1.4800856
View online: http://dx.doi.org/10.1063/1.4800856
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v113/i14
Published by the AIP Publishing LLC.

JOURNAL OF APPLIED PHYSICS **113**, 144306 (2013)

Length and temperature dependent 1/*f* noise in vertical single-walled carbon nanotube arrays

Robert A. Sayer,[1] Jeffrey D. Engerer,[1] N. S. Vidhyadhiraja,[2] and Timothy S. Fisher[1]
[1]*School of Mechanical Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*Theoretical Sciences Unit, Jawaharlal Nehru Center for Advanced Scientific Research, Bangalore, Karnataka, India*

(Received 24 January 2013; accepted 25 March 2013; published online 10 April 2013)

We report measurements of temperature- and length-dependent 1/*f* noise in vertical single-walled carbon nanotube (SWCNT) arrays. Carbon nanotubes are synthesized in a porous anodic alumina template with sub-micrometer channel lengths ranging from 100 to 700 nm. A significant difference is observed in the 1/*f* noise magnitude of quasi-ballistic and diffusive SWCNT devices, with quasi-ballistic devices exhibiting 1/*f* noise levels that are one to two orders of magnitude less than diffusively conducting devices. Furthermore, 1/*f* noise was measured from 90 to 400 K, and the noise prefactor decreased significantly at temperatures below 250 K. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4800856]

I. INTRODUCTION

Carbon nanotubes (CNTs) exhibit mechanical, thermal, and electrical properties that make them well-suited for numerous applications. For example, the excellent electrical properties of single-walled carbon nanotubes (SWCNTs) such as high current carrying capacity and ballistic transport make them candidates for both interconnects and transistors depending on their metallic or semiconducting behavior. However, at the small scales of SWCNTs, 1/*f* noise, which in its simplest form is inversely proportional to the number of carriers in a system, can be quite large such that it may potentially limit the applicability of these devices. In this work, we seek to quantify 1/*f* noise from the ballistic to diffusive regime for CNT arrays in order to correlate length and temperature effects to specific noise regimes and therefore elucidate the profound effects of the diffusive-ballistic transition.

The first major investigation into 1/*f* noise in CNTs was conducted by Collins *et al.*[1] Here, the noise voltage spectral density S_V from individual SWCNTs as well as thin films and bulk mats of SWCNTs was found to follow:

$$S_V = \frac{AV^2}{f^\beta}, \quad (1)$$

where f is frequency, V is the applied voltage, A is the noise prefactor, and β is a constant. Typically, A is inversely proportional to the number of carriers in the system[2] and $\beta = 1.0 \pm 0.1$.[3] The noise prefactor was found to be four to ten orders of magnitude greater than that exhibited by conventional conductors. Additionally, the noise prefactor depended solely on electrical resistance, with which it was directly proportional, for all tested devices such that $A = 10^{-11} R$.

Snow *et al.*[4] continued experimental investigation into 1/*f* noise of SWCNT networks. Although the measured magnitude of the prefactor was similar to that of Collins *et al.*,[1] the authors found that not only does the noise prefactor depend on resistance but it also depends on CNT length, with longer SWCNT networks yielding lower noise prefactors. An empirical formula was suggested for the geometric scaling of 1/*f* noise in these devices ranging in length from 2 μm to 5 mm as $A = 9 \times 10^{-11}\, R/L^{1.3}$.

The foregoing studies reported only the room-temperature 1/*f* noise in SWCNT devices. Temperature-dependent 1/*f* noise of individual SWCNTs was first measured by Kingrey *et al.*[5] for devices in a variety of gas and liquid environments from 77 to 450 K. Although the ambient environment was found to have a minimal effect on the noise prefactor, temperature was shown to impact 1/*f* noise profoundly, with a local maximum near room temperature. When the temperature was increased from this value, the noise prefactor continually decreased. When temperature decreased from room temperature, the noise prefactor dropped to a minimum near 200 K. Further reductions in temperature lead to an increased noise prefactor. A similar trend was noted by Behnam *et al.*[6] in the temperature range from 1–300 K. The noise prefactor was found to have a maximum at about 250 K and a minimum value at 40 K in the SWCNT films.

In this paper, we present both length- and temperature-dependent 1/*f* noise measurements on vertical SWCNT arrays grown in porous anodic alumina (PAA) templates. The PAA template enables fabrication of devices with nanometer lengths from 100 to 700 nm, well below the micrometer and millimeter length devices studied in previous reports. Devices below 300 nm exhibit significant noise reduction which is attributed to quasi-ballistic transport.

II. EXPERIMENTAL PROCEDURE

Vertical arrays of SWCNTs with channel lengths from 100 to 700 nm were grown in a PAA template with an embedded Fe catalyst layer according to a process previously reported.[7,8] The fabrication process is depicted in Fig. 1 through both schematics and field-emission scanning electron microscope (SEM) images. On a Si substrate, the following film stack is thermally evaporated: 100 nm Ti/100 nm Al/1 nm Fe/100 to 700 nm Al, where the thickness of the top Al layer is equal to the desired SWCNT length. The samples are then anodized at 40 V in 0.3 M oxalic acid until the current decreases from the range of several milliamperes to several microamperes, indicating the complete anodization of the Al layers to form PAA as shown in Fig. 1(a). The PAA template consists of pores that are approximately 20–25 nm in diameter with an interpore spacing of 100 nm, yielding a density of 115 pores/μm^2.

Microwave plasma-enhanced chemical vapor deposition (MPCVD) is subsequently used to synthesize the SWCNTs,[9] which nucleate at the embedded Fe layer within the pores and grow vertically in the template with a yield of not more than one SWCNT per pore, as reported previously[9,10] and then extend from the pores and grow across the surface of the PAA as shown in Fig. 1(b). It should be noted that the Fe catalyst used here is thinner than in a previously study, and that this catalyst is expected to predominantly yield SWCNTs by decreasing the catalyst particle size.[11] The SWCNTs were grown by heating the PAA substrate to 900 °C and flowing 50 sccm H_2 and 10 sccm CH_4 at 10 Torr over the sample. CNT growth times were varied for each length sample (growth times ranged from 2 to 12 min; longer channel lengths require longer growth times) in order to provide CNT densities that were approximately equal in each sample. The SWCNT density is estimated from electrical measurements to be approximately 0.4 SWCNTs/μm^2. SEM images of the SWCNTs growing from the PAA template are shown in Figs. 1(e) and 1(f). Electrodeposition of Pd nanowires (Fig. 1(c)) into the pore bottoms serves as a bottom contact to the SWCNTS.[12] Maschmann *et al.*[10] showed that because the CNTs are not contacted initially, the Pd fills the pores from the bottom, up to a point of reaching a very abrupt electrodeposition voltage "signature" at which point the CNTs are contacted and the procedure is halted. Top contacts of 3 nm Pd/60 nm Ti/40 nm Au are deposited via electron beam evaporation to complete the devices (Figs. 1(d) and 1(g)). The inset of Fig. 1(g) shows a tilted cross-sectional SEM image of the finished device. It is clear that the Pd nanowires extend up to the Fe break line in the PAA, making contact to the CNTs, but the Pd does not fill the channel length. The final devices all had resistances that were close to 50 Ω in order to minimize internal reflection from impedance mismatch[13] and minimize the effect of device resistance on the measured noise.

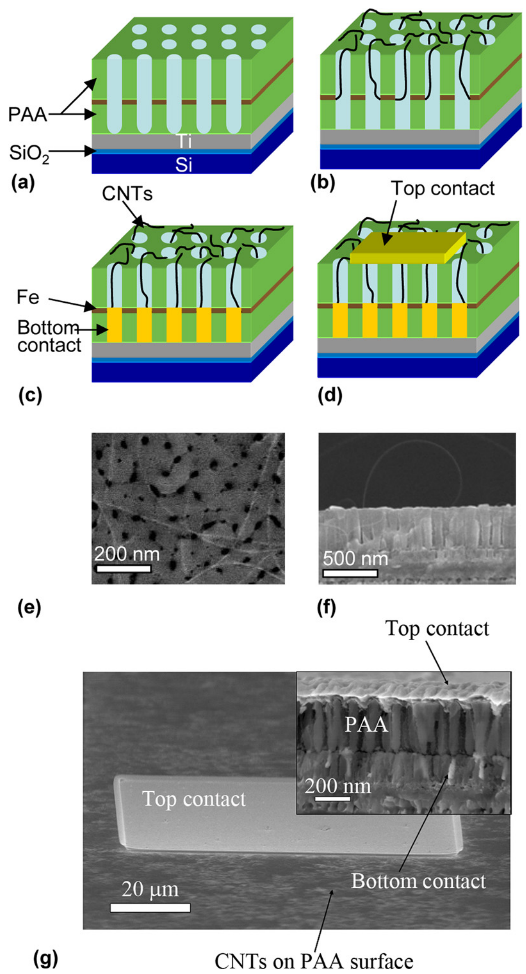

FIG. 1. Fabrication procedure for the SWCNT devices. (a) PAA with an embedded Fe layer is used as a template. (b) SWCNTs are grown at a density of no more than one per pore and (c) Pd nanowires are deposited. (d) A top contact is evaporated to the CNT tips. (e) FESEM image of SWCNTs on the PAA surface. (The SWCNTs appear as white lines in the image.) (f) Cross-section SEM image of the PAA, a SWCNT is shown looping above the surface. (g) Tilted FESEM image of the final device. The 80 $\mu m \times 80\,\mu m$ top contact pad is shown on top of the CNT covered PAA surface. (Inset) Cross-sectional view of the final device. Pd nanowires fill the bottom of the pores and provide a bottom contact to the CNTs.

The noise measurement system, consisting of both DC and radio frequency (RF) circuitry, is shown schematically in Fig. 2. The DC circuitry consists of a current source that has the output connected to two bias T's that are in series in order to minimize source noise. The RF output from the bias T is terminated in 50 Ω, while the DC output used to bias the device under test (DUT), which is packaged in a electromagnetic interference (EMI) shielded die cast aluminum alloy box. The voltage noise fluctuations across the device are then measured using the RF circuitry. A DC block is used to isolate the RF components. The signal is amplified using a RF low noise amplifier (LNA). A bandpass filter is then used to prevent aliasing of the data. A high-speed digitizer records the data, which is post-processed in MATLAB.

III. RESULTS AND DISCUSSION

Unlike previously reported 1/*f* noise measurements for CNT devices that lie on an oxide substrate, in this study, the CNTs are oriented vertically in a PAA template. Reza *et al.*[14] found no change in the magnitude of the noise prefactor for SWCNT devices supported on an oxide layer or suspended over a trench. Similarly, the change in support structure from planar to vertical is expected to have negligible effect on the 1/*f* noise magnitude. The tested devices, which each had a resistance of about 50 Ω in order to minimize internal reflection from impedance mismatch,[13] were biased from 0 to 200 mV. Electrical contact was made to each device via two different top contacts, such that the measured device is actually two CNT arrays connected

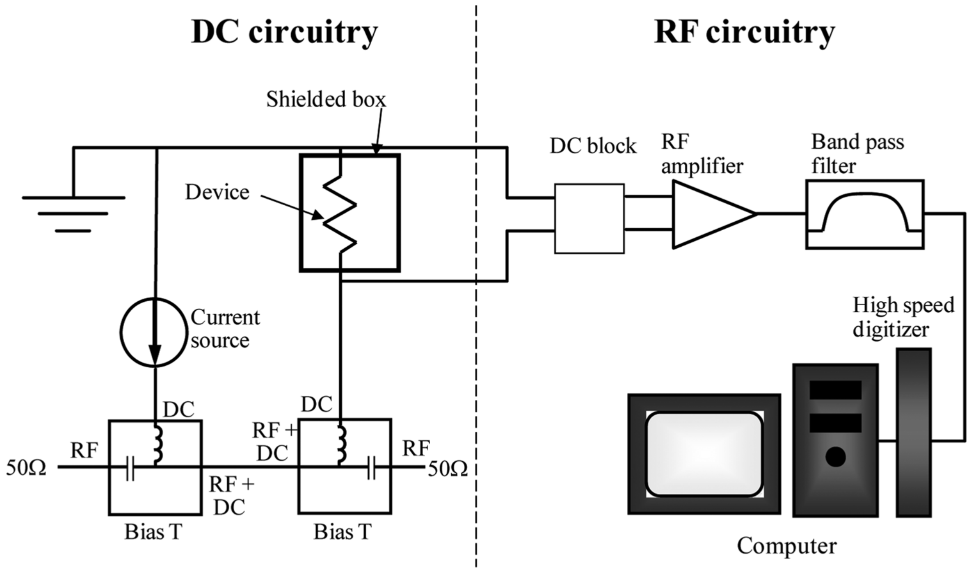

FIG. 2. Schematic showing both the DC and RF circuitry of the noise measurement system.

electrically in series (the top contacts were spaced sufficiently far apart as to mitigate conduction across the CNT network on the surface of the PAA). The noise spectral density is proportional to the square of voltage and hence the square of the total resistance. Assuming that the resistance of both CNT arrays is equal the measured noise is a factor of four times greater than that of a single array. However, the voltage drop across each array is one half of the total applied bias. Accounting for this reduction, it can be shown that the noise prefactor of the overall device is the same as the noise prefactor from each array, and therefore, the geometry has negligible influence on the obtained results. Noise spectra (1600 averages) for a typical vertical SWCNT/PAA device in the frequency band from 1 to 100 MHz are shown in Fig. 3. The inset of Fig. 3 shows the noise voltage spectral density measured as a function of the square of the applied bias for three different frequencies (1, 2, and 3 MHz). The spectral density of the noise increases linearly with the square of the applied bias, as expected for a $1/f$ dominated noise signal describe by Eq. (1).

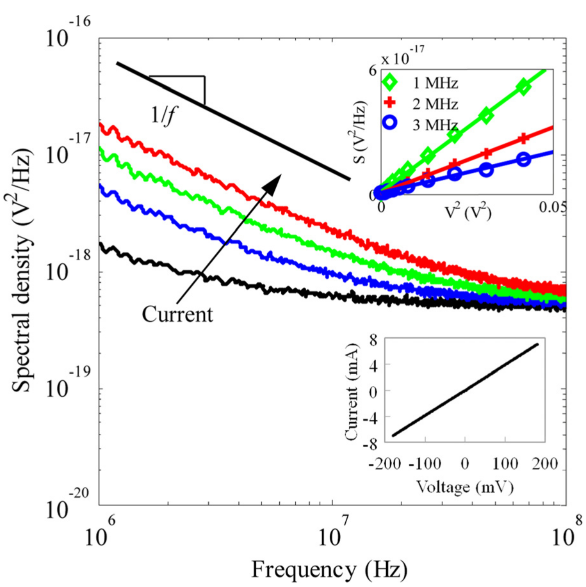

FIG. 3. Noise spectra for a typical vertical SWCNT/PAA device in the frequency band from 1 to 100 MHz. (Top inset) Noise voltage spectral density of a typical device at four different frequencies as a function of the square of the applied voltage. (Bottom inset) *I-V* curve of a 200 nm channel length device.

The noise from a total of 15 different SWCNT devices with five different channel lengths (100, 200, 320, 400, and 700 nm) was measured. Previous studies have shown that the external environment can influence the noise signal of a CNT.[5,15,16] Although the top contacts were deposited under vacuum, the final devices were exposed to atmospheric conditions for sufficiently long time that air likely diffused into the pores. Figure 4 shows the $1/f$ noise prefactor measured for each device. When the CNT channel length falls below 300 nm, a large reduction in the noise prefactor is observed. Because $1/f$ noise scales inversely with the number of carriers, one would expect noise spectral density to increase monotonically as the CNT channel length decreases. In fact, Snow *et al.*[4] reported increased noise with length reductions of three orders of magnitude from 5 mm channel lengths down to 2 μm. However, the sub-micron channel length devices used in this study enable measurement of two different

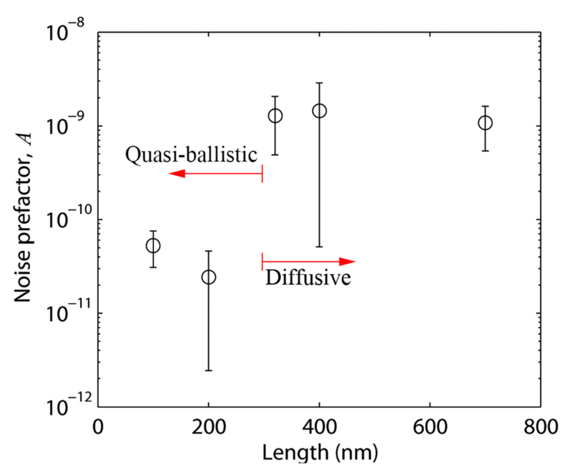

FIG. 4. Noise prefactor measured at 294 K for CNT devices ranging in length from 100 to 700 nm. *A* is found from an average of nine different voltage values between 10 and 200 mV.

transport regimes in the CNTs—quasi-ballistic and diffusive. Javey *et al.*[17] showed that CNTs with lengths below 300 nm exhibit predominantly ballistic (i.e., quasi-ballistic) transport behavior (at room temperature) regardless of diameter. Here, the nearly two order of magnitude reduction in noise between the 320 and 200 nm devices is attributed to a transition of electron transport in the device from diffusive to quasi-ballistic.

Tersoff[18] proposed a model for 1/*f* noise in nanoscale ballistic transistors based on measurements conducted on 200 nm CNT Schottky-barrier field-effect transistors. The noise prefactor can depend on a host of the factors including the energetic distribution of traps, the nature of scattering and hence the temperature as well. For CNT arrays in the ballistic regime, it was shown that the noise prefactor is no longer dependent on the number of carriers.[18]

Next, the noise prefactor and electrical resistance were measured over temperatures ranging from 90 to 400 K for the 100 nm, 200 nm, 320 nm, and 400 nm channel length CNT devices as shown in Fig. 5. As shown in Fig. 4, the shorter devices exhibited small values of 1/*f* noise in comparison to longer devices. Because of the large difference in the magnitude of *A*, the values for each device have been normalized to their measured values at 294 K. Below 250 K, 1/*f* noise decreases with temperature to a value 40 times less than the peak value in the shorter (100 nm and 200 nm) devices and a value 20 000 times less in the longer (320 nm and 400 nm) devices. Above 250 K, the 1/*f* noise tends to slightly increase as temperature rises to up to 400 K. This trend is similar to that measured by Behnam *et al.*[6]

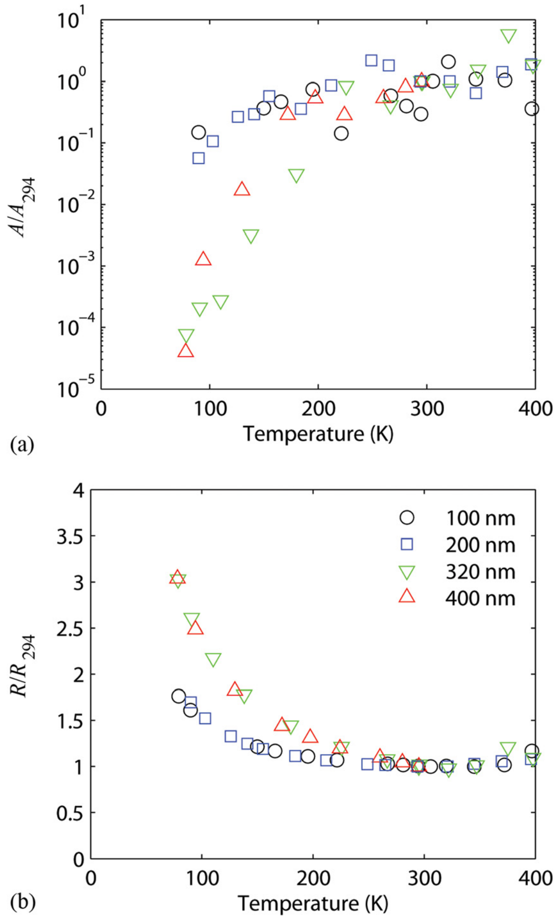

FIG. 5. Temperature dependent (a) noise prefactor and (b) electrical resistance measured for CNT devices with channel lengths from 100 nm to 400 nm. Due to the large difference in the magnitude of A for the devices, the noise prefactor has been normalized to the measured value at 294 K. *A* is found from an average of nine different voltage values between 10 and 200 mV.

The SWCNT arrays tested involve a combination of metallic and semiconducting nanotubes connected electrically in parallel. Reza *et al.*[19] developed a method for separately measuring the 1/*f* noise contribution from semiconducting and metallic CNTs connected electrically in this manner. The noise prefactor of the semiconducting CNTs was found to be an order of magnitude greater than that of the metallic CNTs. Additionally, Lin *et al.*[20] found that gate voltage can drastically affect 1/*f* noise in semiconducting CNTs. It should be noted that in the SWCNT/PAA structures tested here, the semiconducting CNTs have been shown to be electrically "off."[7] Because current flows through the most conductive CNTs, the measured noise signal will be dominated by the metallic nanotubes; therefore, the reported noise prefactor values are representative of the metallic CNTs. The electrical resistance of the SWCNT arrays decreases continuously with increasing temperature. This trend has been observed in SWCNT[21] and multi-walled CNT (MWCNT)[22] yarns and sheets, as well as individual MWCNTs.[23] Although this trend is representative of typical semiconducting devices, Barnes *et al.*[21] showed that a majority of semiconducting or metallic SWCNTs in a network does not yield the typical semiconducting or metallic resistance dependence. In fact, it was found that the transition to a region where $dR/dT > 0$, which is typically associated with metallic behavior, is not observed in undoped metallic SWCNT films (the maximum test temperature was 450 K). Rather, $dR/dT > 0$ is caused by dopant desorption at elevated temperatures in both semiconducting and metallic SWCNTs.

The device resistances measured here will be a combination of both the resistance of the CNTs in the array and the contact resistance between the CNTs and the Pd contacts. Not only is the resistance of the SWCNTs in the array expected to decrease with increasing temperature but so too is the contact resistance.[23,24] As shown in Fig. 5(b), the 320 and 400 nm devices and the 100 and 200 nm devices exhibit similar resistance changes with temperature. The resistance of the 320 and 400 nm devices decreases by a factor of 3 as temperature increases from 90 K to room temperature. However, the resistance of the 100 and 200 nm devices changes by only a factor of two. In the short devices (100 and 200 nm), electron transport is primarily limited by the contacts[25,26] and as a result, the SWCNTs have little effect on the overall resistance. Owing to the resistance being only weakly coupled to that of the CNTs, the rate of change of resistance with temperature is thus less for the short devices.

IV. CONCLUSION

In summary, the temperature and length dependence of 1/*f* noise in vertical, sub-micron length SWCNTs has been experimentally investigated. The noise prefactor was found to decrease significantly when the CNT channel length in the array was decreased below 300 nm, which is attributed to quasi-ballistic electron transport in the CNTs. Furthermore, the noise prefactor was found to decrease significantly below 250 K. Above 250 K, the noise prefactor had a weak dependence on temperature. Knowledge of 1/*f* noise in CNTs is not only important for the design of sensors and electronic components, but accurate characterization also enables measurement of shot noise and self-heating in these systems in frequency bands that are not possible using conventional measurements.[27]

ACKNOWLEDGMENTS

This material was based upon work supported by the NNSA Center for Prediction of Reliability, Integrity, and Survivability of Microsystems under Award No. DE-FC52-08NA28617.

[1] P. G. Collins, M. S. Fuhrer, and A. Zettl, Appl. Phys. Lett. **76**, 894–896 (2000).
[2] F. N. Hooge, Phys. Lett. A **29**, 139–140 (1969).
[3] F. N. Hooge, IEEE Trans. Electron Devices **41**, 1926–1935 (1994).
[4] E. S. Snow, J. P. Novak, M. D. Lay, and F. K. Perkins, Appl. Phys. Lett. **85**, 4172–4174 (2004).
[5] D. Kingrey, O. Khatib, and P. G. Collins, Nano Lett. **6**, 1564–1568 (2006).
[6] A. Behnam, A. Biswas, G. Bosman, and A. Ural, Phys. Rev. B **81**, 125407 (2010).
[7] A. D. Franklin, R. A. Sayer, T. D. Sands, D. B. Janes, and T. S. Fisher, IEEE Trans. Nanotechnol. **8**, 469–476 (2009).
[8] R. A. Sayer, S. Kim, A. D. Franklin, S. Mohammadi, and T. S. Fisher, IEEE Trans. Compon. Packag. Technol. **33**, 178–183 (2010).
[9] M. R. Maschmann, A. D. Franklin, P. B. Amama, D. N. Zakharov, E. A. Stach, T. D. Sands, and T. S. Fisher, Nanotechnology **17**, 3925–3929 (2006).
[10] M. R. Maschmann, A. D. Franklin, A. Scott, D. B. Janes, T. D. Sands, and T. S. Fisher, Nano Lett. **6**, 2712–2717 (2006).
[11] M. R. Maschmann, A. D. Franklin, T. D. Sands, and T. S. Fisher, Carbon **45**, 2290–2296 (2007).
[12] A. D. Franklin, M. R. Maschmann, M. DaSilva, D. B. Janes, T. S. Fisher, and T. D. Sands, J. Vac. Sci. Technol. B **25**, 343–347 (2007).
[13] L. Spietz, K. W. Lehnert, I. Siddiqi, and R. J. Schoelkopf, Science **300**, 1929–1932 (2003).
[14] S. Reza, Q. T. Huynh, G. Bosman, J. Sippel-Oakley, and A. G. Rinzler, J. Appl. Phys. **99**, 114309 (2006).
[15] I. Heller, J. Mannik, S. G. Lemay, and C. Dekker, Nano Lett. **9**, 377–382 (2009).
[16] M. Ishigami, J. H. Chen, E. D. Williams, D. Tobias, Y. F. Chen, and M. S. Fuhrer, Appl. Phys. Lett. **88**, 203116 (2006).
[17] A. Javey, J. Guo, Q. Wang, M. Lundstrom, and H. Dai, Nature **424**, 654–657 (2003).
[18] J. Tersoff, Nano Lett. **7**, 194–198 (2007).
[19] S. Reza, Q. T. Huynh, G. Bosman, J. Sippel-Oakley, and A. G. Rinzler, J. Appl. Phys. **100**, 094318 (2006).
[20] Y.-M. Lin, J. Appenzeller, Z. Chen, and P. Avouris, Physica E **37**, 72–77 (2007).
[21] T. M. Barnes, J. L. Blackburn, J. van de Lagemaat, T. J. Coutts, and M. J. Heben, ACS Nano **2**, 1968–1976 (2008).
[22] M. Zhang, S. Fang, A. A. Zakhidov, S. B. Lee, A. E. Aliev, C. D. Williams, K. R. Atkinson, and R. H. Baughman, Science **309**, 1215–1219 (2005).
[23] A. Bachtold, M. Henny, C. Terrier, C. Strunk, C. Schonenberger, J. P. Salvetat, J. M. Bonard, and L. Forro, Appl. Phys. Lett. **73**, 274–276 (1998).
[24] S. M. Sze, *Physics of Semiconductor Devices* (John Wiley & Sons, 1981).
[25] S.-J. Choi, P. Bennet, K. Takei, C. Wang, C. C. Lo, A. Javey, and J. Bokor, ACS Nano **7**, 798–803 (2013).
[26] A. D. Franklin and Z. Chen, Nat. Nanotechnol. **5**, 858–862 (2010).
[27] R. A. Sayer, J. D. Engerer, S. Sen, N. S. Vidhyadhiraja, and T. S. Fisher, in *ASME International Mechanical Engineering Congress and Exposition* (Denver, CO, 2011), pp. IMECE2011-63586.